PARAMETRIC STUDY OF OHMIC WALL HEATING IN COAXIAL CAVITY

Ashok Kumar[1] and Manjeet Singh[2]

[1]*Singhania University, Rajasthan, India*

[2]*Amity University, Noida, U.P, India*

ABSTRACT

A detail parametric study related to Ohmic wall loading for coaxial insert of 2 MW, 140 GHz coaxial gyrotron is discussed in this manuscript. Corrugation is done in the coaxial insert to minimize the Ohmic wall loading. The geometry of corrugated coaxial insert seriously affects the Ohmic wall loading in a gyrotron. Ohmic wall loading is critical especially for multi-megawatt high frequency gyrotrons. Considering all these facts,a detail parametric study of coaxial insert is performed for 140 GHz coaxial gyrotron in this article.

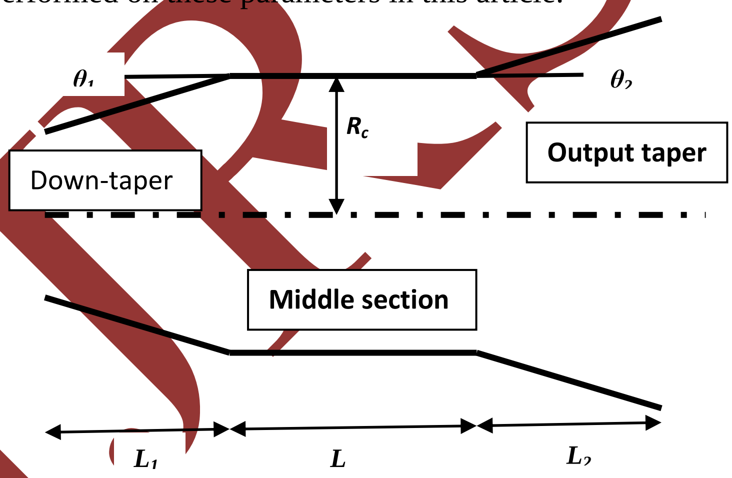
Keywords: *Coaxial, Ohmic Wall loading, coaxial insert*

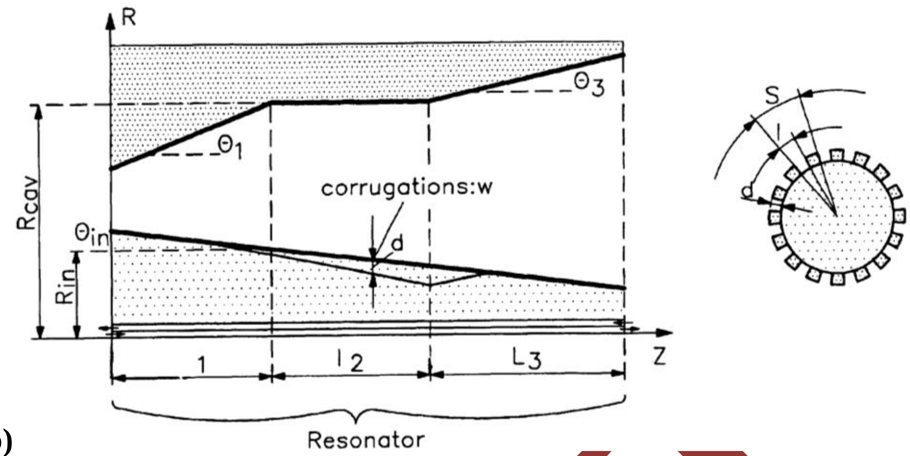
INTRODUCTION

Considering the increasing demand of the energy and the regular depletion of the conventional energy sources, the research work on the various novel renewable energy sources is going on worldwide intensively. Among the various renewable energy sources, the energy generation by plasma fusion is getting popularity due to its various advantages over conventional and non-conventional energy sources. Various research groups including IPR Gandhinagar, India are involved in the research of efficient energy generation by magnetically confined plasma. International Thermonuclear Experimental Reactor is an international effort in the direction of energy generation by plasma fusion [1,2]. For the energy generation, confined plasma is heated up to millions of degree centigrade so that fusion reaction can start. For plasma heating, various types of RF sources are used including gyrotron. Gyrotron oscillator is the only device at present which is capable to deliver MW RF power in the millimeter wave band and thus are used as the RF power source in almost all plasma fusion reactors. Gyrotron is a vacuum based microwave generation device based on the phenomena called CRM (Cyclotron Resonance Maser) instability occurred during the beam-wave interaction [3,4]. At present, gyrotron is a signature device for ECRH in magnetically confined plasma fusion. Such gyrotrons are called fusion gyrotrons and these devices differ than other low power or high frequency gyrotrons. Major features of fusion gyrotrons are very high RF power (> 1 MW), high frequency (> 100 GHz), and high efficiency (> 40 %) [5.6]. To achieve these features, very high order transverse electric (TE) mode is selected as the operating mode for fusion gyrotron [7]. One major part of any gyrotron is the interaction cavity where the beam-wave interaction takes place. In general, simple cylindrical open interaction cavity (Fig. 1a) is used for MW class millimeter wave gyrotrons. The interaction cavity in gyrotron consists three parts (as shown in Fig. 1a), down taper (cut-off region), middle section and up-taper section (travelling wave region). In case of much higher RF power (*e.g.* 2 MW or more), the cylindrical open interaction cavity starts to show serious problem of ohmic wall loading as well as space charge effect [8,9]. The ohmic wall loading can be reduced by selecting the very high order TE mode, but in this case the mode competition becomes an uncontrolled problem. On the other hand, high beam current is required to get much higher RF power, which further enhances the space charge effect of the transported electron beam. Considering all these issues in multi-MW gyrotrons, the coaxial insert is used in the cylindrical cavity (Fig. 1b) and this whole structure is called coaxial cavity. The detail discussion on coaxial cavity is performed in a review article [10,11].

Here in this article, the parametric study of Ohmic wall loading for coaxial insertin coaxial cavity of 140 GHz, 2 MW gyrotron is performed. Table 1 shows the design parameters of 140 GHz coaxial gyrotron. The voltage depression, limiting current, ohmic wall loading at cavity wall and at different part of coaxial insert are major design parameters of the coaxial cavity. The detail discussion is performed on these parameters in this article.

(a)





(b)

Fig. 1: (a) simple cylindrical cavity, **(b)** Coaxial cavity [10].

Table 1: Design specifications of coaxial 140 GHz gyrotron

Frequency	140 GHz
Power	2 MW
Interaction efficiency	>30 %
Beam voltage	90 kV
Beam current	70 A
Alpha	1.3
Operating mode	$TE_{31,17}$

OHMIC LOSSES

Ohmic wall loading is a major parameter in the design of interaction cavity and TE mode selection. Some of the electromagnetic power in the interaction cavity is dissipated in the form of ohmic heating in the cavity material. The loss in the electromagnetic power is defined in terms of the ohmic wall loss (heat dissipated in per unit area). The ohmic wall loading at different parts of gyrotron coaxial cavity is given by the following expressions [13,14].

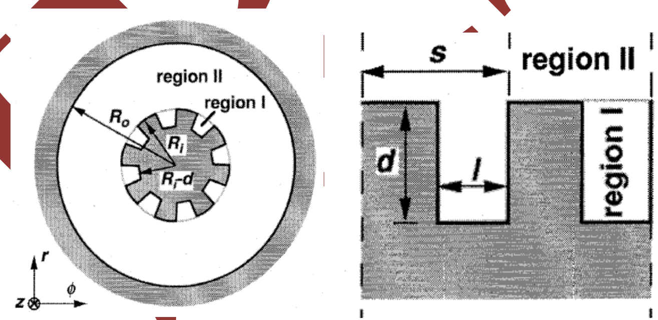
$$\rho_{cavity} = \frac{2\pi^2\delta}{0.625L\lambda^2} Z_{mp}^2\left(\chi_{mp}\right)C_{mp}^2 Q_{diff} P_{out} \qquad (3)$$

$$\rho_{i,top} = \frac{2\pi^2\delta}{0.625L\lambda^2} Z_{mp}^2\left(\frac{\chi_{mp}}{C}\right)C_{mp}^2 Q_{diff} P_{out} \qquad (4)$$

$$\rho_{i,side} = \frac{\rho_{i,top}}{\cos^2\left(\dfrac{\chi_{mp}}{C}\right)} \cos^2\left(\frac{\chi_{mp} x}{R_c}\right) \qquad (5)$$

$$\rho_{i,bottom} = \frac{\rho_{i,top}}{\cos^2\left(\dfrac{\chi_{mp}}{C}\right)} \qquad (6)$$

Here, C=R_c/R_i, δ is the skin depth calculated for OFHC copper material, L is the length of cavity middle section, $Z_{mp}$is the cylindrical function, $C_{mp}$is a normalized constant. Further,$Z_{mp}$and $C_{mp}$are function of Bessel and Neumen functions offirst order and the geometry of corrugated insert [13,14]. The corrugated insert is used in cylindrical cavity to minimize the ohmic wall loading and for the surface impedance matching. l, s, and d are the width of corrugation, period of corrugation and depth of corrugation , respectively (Fig. 2). Equation (3) gives the ohmic wall loading at the wall of cylindrical waveguide of co-axial cavity (ρ_{cavity}). Similarly equations (4), (5) and (6) are for the ohmic wall loading at the top, side and bottom of the coaxial insert respectively. The cavity radius and beam radius directly depends on the selected operating mode (χ_{mp} is the root of Bessel function derivative, which is a parameter of TE_{mp} mode). So in conclusion it can be said that the voltage depression and limiting current in cavity directly depends on the operating mode. Various TE modes are analyzed in terms of voltage depression and limiting current and finally $TE_{31,17}$ mode (χ_{mp}=94.615) is found suitable.



(a) (b)

Fig. 2: Schematic view of corrugated insert rod.

RESULTS AND DISCUSSION

Fig. 3 shows the Ohmic wall loading in kW/cm^2 at cavity wall and coaxial insert. In the calculations, minimum number of corrugations ($N=2\pi R_i/s$, where $s<\pi R_i/m$) are used. The depth (d) of corrugation in the coaxial insert is kept λ/4 for the surface impedance matching. The surface impedance matching with the propagated mode establishes the minimum wall loss at the top surface of coaxial insert. In Fig. 3b, Ohmic wall loading is calculated at different positions of corrugation from bottom to top. It can be seen from figure that the wall loading increases from top (where Ohmic loading is approximately zero due to the surface impedance matching) to bottom (maximum Ohmic loading). The interaction cavity including coaxial insert is made of Oxygen Free High Conductivity (OFHC) copper for which theoretical limit of Ohmic wall loading is 1 kW/cm^2. Including the practical parameters such as surface roughness, temperature dependence of material electrical conductivity, etc., the limit of Ohmic wall loading should be taken twice of the theoretical limit. Considering the constraint of Ohmic wall loading, the geometry of coaxial insert is finalized and given in Table 2.

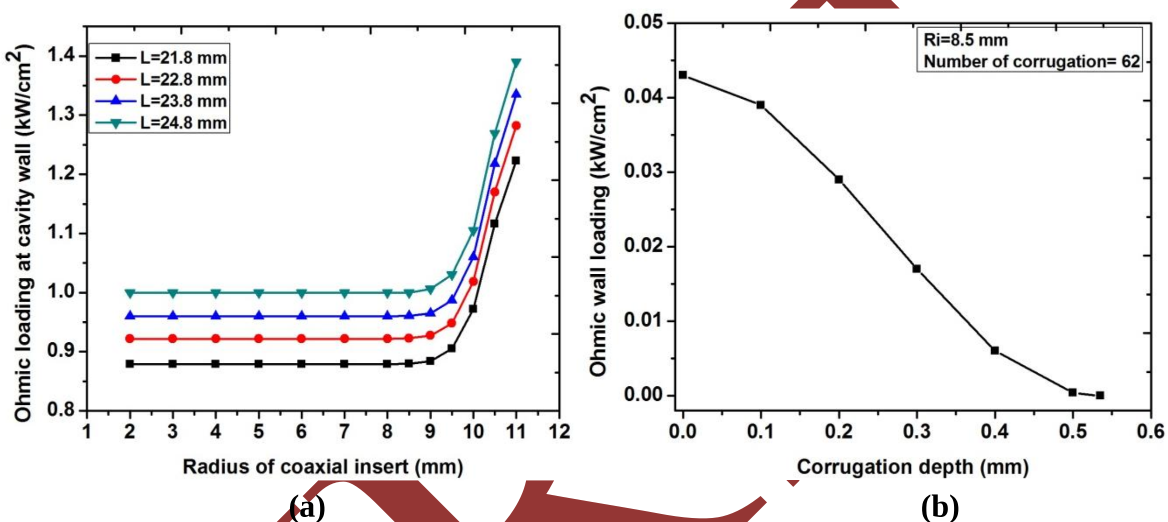


Fig. 3: (a) Ohmic loading at cavity wall with respect to coaxial insert radius for different cavity length, **(b)**Ohmic wall loading at different positions of corrugation depth.

Table 2: Finalized geometry of cavity and coaxial insert

Cavity radius (R_c)	32.28 mm
Cavity length (L)	23 mm
Coaxial insert radius (R_i)	8.5 mm
Depth of corrugation (d)	0.535 mm
Width of corrugation (l)	0.43 mm
Period of corrugation (s)	0.86 mm
Number of slots (N)	62

CONCLUSION

In this article a detail parametric study of Ohmic wall loading at coaxial cavity is performed. Interaction cavity design parameters of Ohmic wall loading at different parts of coaxial insert are calculated with respect to coaxial insert geometry. Based on the constraints of Ohmic wall loadingwhich is < 1 kW/cm^2, the geometry of coaxial insert is finalized for 2 MW, 140 GHz gyrotron coaxial cavity operating at $TE_{31,17}$mode.

REFERENCES

[1] G.S. Nusinovich, M. K. A. Thumm and M. I. Petelin, "The gyrotron at 50: Historical review", *J. Infrared Milli. Terahz.Waves*, vol. 35, pp. 325-381, 2014.

[2] M. Thumm, State of the art of high power gyro-devices and free electron masers update 2012, FZK, KIT, Germany, 2014.

[3] M. Thumm, "Progress in gyrotron development", *Fusion Eng. Design*, vol. 66–68, p. 69, 2003.

[4] M.V. Kartikeyan, E. Borie, M. Thumm, Gyrotrons: High-Power Microwave and Millimeter Wave Technology, Springer, Germany, 2004.Nusinivich.

[5] K.Sakamoto, A. Kasugai, K. Takahashi, R. Minami, N. Kobayashi & K. Kajiwara, "Achievement of robust high-efficiency 1 MW oscillation in the hard-self-excitation region by a 170 GHz continuous-wave gyrotron", *Nature Physics*, vol. 3, pp. 411-414, 2007.

[6] C.J. Edgecombe, Gyrotron Oscillators: Their Principles and Practice, Taylor & Francis, London, 1993.

[7] V. A. Flyagin, A. V. Gaponov, M. I. Petelin, and V. K. Yulpatov, "The gyrotron", *IEEE Tr. Microwave Theory & Technique*, vol. MTT-25, pp. 514-521, 1977.

[8] K. Sakamoto, Y. Oda, R. Ikeda, T. Kobayashi, K. Kajiwara, K. Takahashi and S. Moriyama, "Development of high power gyrotron and related technologies", *Terahertz Science and Technology*, vol. 8, pp. 1-18, 2015.

[9] R.A. Correa and J.J. Barroso.Space Charge Effects of Gyrotron Electron Beams in Coaxial Cavities.*International Journal of Electronics*, Vol. 74:131–136, 1993.

[10] O.Dumbrajs, and G. S. Nusinovich, "Coaxial Gyrotrons: Past, Present, and Future (Review)", *IEEE Tr. Plasma Science*, vol. 32, pp. 934-946, 2004.

[11] M.H. Beringer, Design Studies Towards a 4 MW 170 GHz Coaxial-cavity Gyrotron, PhD Thesis, KIT, Germany.

[13] C.T. Iatrou, "Mode selective properties of coaxial gyrotron resonators", *IEEE Tr. Plasma Science*, vol. 24, pp. 596-6.5, 1996.

[14] C.T. Iatrou, S. Kern, and A.B. Pavelyev, Coaxial cavities with corrugated inner conductor for gyrotrons", *IEEE Tr. Microwave Theory & Techniques*, vol. 44, pp. 56-64, 1996.